GIS-Based Assessment of Soil Erosion Risk in Arid Mediterranean Regions Using the MEDALUS Model: A Case Study of the Boussaada Sub-Basin, Algeria

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ABSTRACT

Soil erosion poses a significant environmental threat, especially in arid and semi-arid regions where both natural conditions and human activities accelerate land degradation. This study assesses the vulnerability of the Boussaâda sub-basin to water erosion by applying the MEDALUS (Mediterranean Desertification and Land Use) model. The analysis incorporates four essential quality indices—Soil Quality Index (SQI), Climate Quality Index (CQI), Vegetation Quality Index (VQI), and Anthropogenic Quality Index (AQI)—derived from remote sensing data, GIS tools, and field observations. Covering an area of 2,938.36 km², the study region features a varied topography, with elevations ranging from 393 to 1,644 meters and slope gradients between 6% and 25%. The results reveal substantial spatial variability in soil quality, with moderate-quality soils dominating (64% of the area), followed by high-quality (21%) and low-quality soils (13%). The erosion sensitivity map illustrates the spatial distribution of at-risk zones, underscoring the significant influence of climate, terrain, and land use on soil degradation. These findings offer critical insights to guide sustainable land management strategies aimed at reducing erosion risk in the region.

Keywords: Erosion sensitivity, Boussaada sub-watershed, MEDALUS, GIS.

INTRODUCTION

Soil erosion remains one of the most pressing environmental issues worldwide, with 65% of global soils facing degradation, including erosion and desertification (Fadl et al. 2022). Climate change and poor agricultural practices are exacerbating soil degradation, including erosion, across the globe (Achim, 2015; Seghiri et al. 2022; Bensefia et al. 2024). These phenomena manifest differently depending on regional and local conditions, and their impacts vary significantly. Key consequences include vegetation loss, expansion of sandy areas, soil impoverishment, reduced agricultural yields, and the deforestation of agricultural species

(Madani et al. 2023). While developed countries are not immune, soil erosion presents a particularly severe threat to developing nations. In Africa, approximately 12.5 million hectares of soil are at risk from wind and water erosion (Pushpam et al. 2015). In Algeria, particularly in mountainous regions, escalating erosion is significantly deteriorating local living conditions and causing severe consequences (Meddi et al. 2005). This erosion leads to an estimated annual loss of 20 million cubic meters of water storage in dams due to siltation(Remini 2000). Over time, this erosion reduces soil fertility and decreases biodiversity, undermining agricultural productivity, which is crucial for the livelihood of many people who rely on this resource (Khali et al. 2016). The socio-economic impacts are also significant, with erosion contributing to floods that endanger both populations and infrastructure (Roose et al. 2010).

A variety of methods and approaches have been introduced over the decades to study water erosion, such as the Universal Soil Loss Equation (USLE) (Cherif 2008), the modified version by Foster et al. (1987) cited by Lalfen et al. (1991), the water erosion prediction project (Tra Bi 2013), and the MEDALUS approach (Plaiklang et al., 2020). The arid and steppe regions of northern Sahara, covering more than 600,000 km², include approximately 34% of Algeria (Le Houérou 1995). Recently, the Algerian steppe has experienced an ecological and climatic imbalance, marked by significant degradation of its fragile environment (Liazid 2013). Climatic variability places constant stress on ecosystems, and this pressure increases as one moves southward (Benmessaoud 2009). The southern Hodna region has particularly witnessed a dramatic transformation due to sand encroachment, exacerbated by external factors like erosion and desertification. This situation presents significant challenges for local inhabitants (Abdesselam &Halitim 2014). The degradation is widespread, leading to deterioration of the region's vital natural spaces despite their importance in human life and their role in microclimate regulation (Seghiri et al. 2022; Ouzir 2023).

To quantify and assess the severity of soil erosion, various methods have been implemented, including the MEDALUS model (Plaiklang et al. 2020), which is frequently used in Algeria. The aim of this study is to assess the factors contributing to soil degradation in the endorheic Hodna basin, with particular attention to the influence of both natural factors, such as the arid climate and sporadic rainfall, and anthropogenic factors, including overgrazing, deforestation, and forest fires. Specifically, the goal is to create an erosion sensitivity map using the MEDALUS method and GIS tools. The study will first describe the physical characteristics of the region, review the methods used, and then interpret the results to analyze the erosion phenomenon. This study will contribute a valuable erosion sensitivity map that can greatly aid in evaluating the degradation status of the Hodna basin.

METHODOLOGY

Study area

The Boussaada sub-basin, located in the south western part of the Hodna watershed, covers 2938.36 km². It consists of three sub-basins: Maiter downstream (1263.05 km²), Boussaâda(1018.81 km²), and Maiter upstream (1263.05 km²) (Fig. 1). The sub-basin is positioned between 35°27'2.4013" N and 34°47'21.0125" S, and 3°35'56.3117" W and 4°31'7.7631" E.

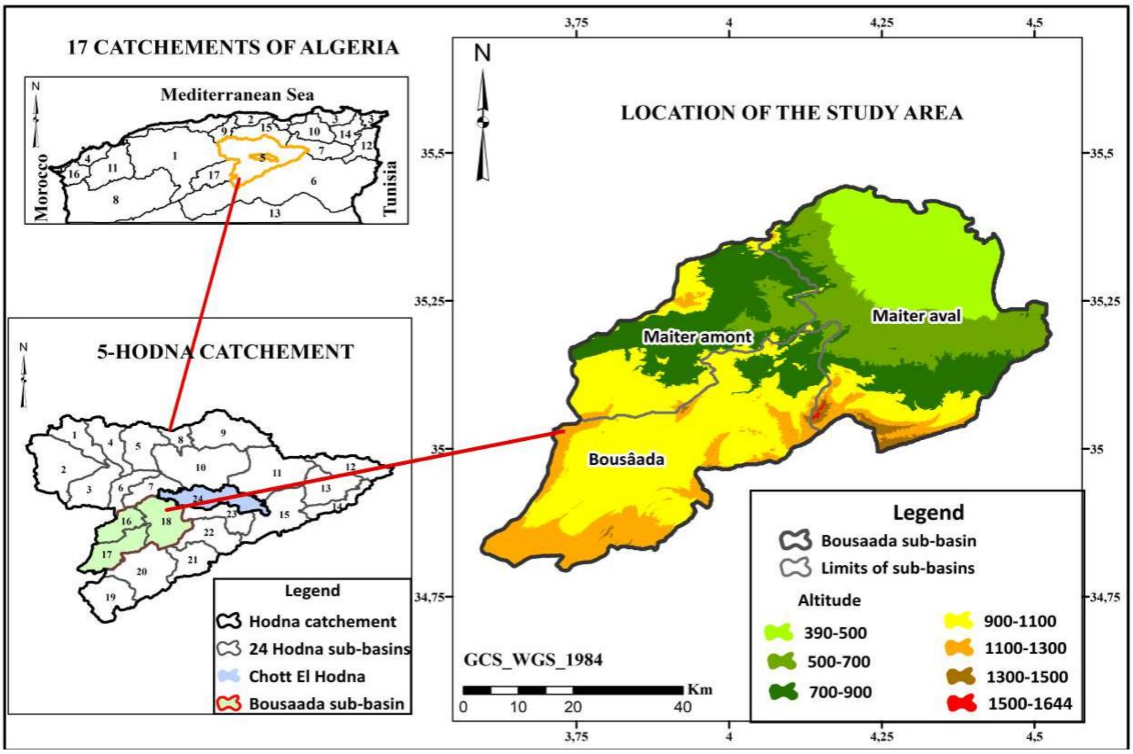


Figure1. Study area

The altitude of the area ranges from 393 to 1644 meters, from north to south, with slopes varying from gentle to moderate, ranging between 6% and 25% (Tab. 1 & Fig. 2).

Table1. Morpho-hydrographic characteristics of the Boussaada sub-basin

Characteristic	Symbol	Unit	Value
Watershed area	A	Km²	2938,36
Perimeter	P	Km	317,87
The length of the basin	L	Km	96,8
The width of the basin	I	Km	30,35
Form factor	K	/	1,64
Maximum altitude	H_{max}	m	1644
Minimum altitude	H_{min}	m	393
Average slope	I_m	m/Km	119,88
The length of the main river	L_p	Km	102,8
Drainage density	D_d	Km/Km²	0,16
Source: Personal analysis in Arc gis software.			

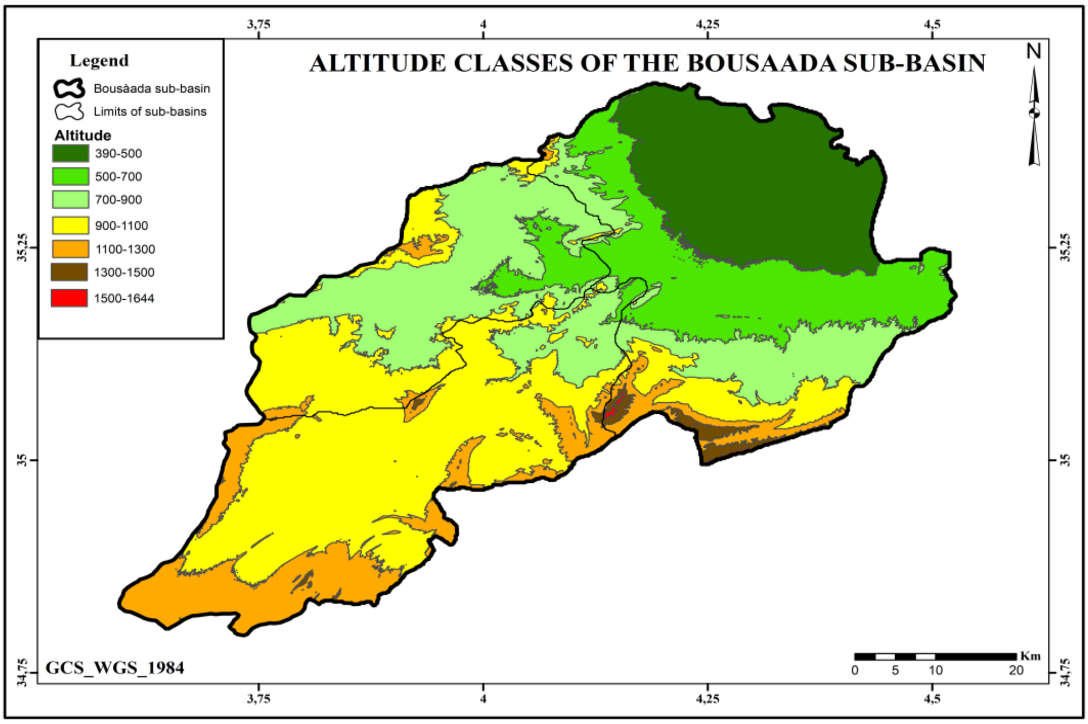


Figure2: Altitude classes of the Boussaada sub-basin

MATERIALS AND METHODS

Data and materials used

To build and improve our database and prepare the necessary thematic layers for the MEDALUS model, we collected data on various variables that influence erosion. These data were sourced from available information in the study area and integrated into a GIS. The materials and data required for this study are summarized in Table 2 below. These data were used to calculate the following indices: Soil Quality Index (SQI), Climate Quality Index (CQI), Vegetation Quality Index (VQI), Anthropogenic Quality Index (AQI), and ultimately the Erosion Sensitivity Index (ESI) (Tab. 2 & Fig. 4).

Table 2: Materials used

Data/Documents	Software
Landsat 8 TM satellite image (March 2024, 30 m)	Envi 5.4 Arc GIS 10.8 Global Mapper Version 15.1
Digital Elevation Model (DEM) of the Boussaâdasub-basin (Landsat 8 TM)	
Soil map of Hodna, 1/500,000 by [FAO 2024]	
Map of hydro-climatic networks and water quality monitoring	
Monography of the Wilaya of M’sila, 1/500,000 [DPSB, 2020]	
Static data of the Wilaya of M’sila [DSA, 2020]	
Climatic data of the Wilaya of M’sila [ANRH, 2020]	

FAO: FAO, 2025. FAO-UNESCO Soil Map of the World and Soil Databases. Food and Agriculture Organization of the United Nations. Consulted on 2025, https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases / faounesco-soil-map-of-the-world/en/.
DPSB–Directorate of Programming and Budget Monitoring-Msila.: 2020.
DSA: Department of Agricultural Services.: 2020.
ANRH: National Agency of Hydraulic Resources. 2020.

Applied Methodology - Evaluation of MEDALUS Model Parameters

The methodology of this study follows the MEDALUS model, which evaluates erosion sensitivity by calculating the geometric mean of quality indices derived from both environmental and human activity factors. These include soil, climate, vegetation, and land use planning (Plaiklang et al., 2020). These parameters are recognized for their influence on soil degradation, as outlined by Fadl et al. (2022).

The main objective of this study is to develop an erosion sensitivity map by using four primary variables: soil, vegetation, climate, and human activities, to calculate the Erosion Sensitivity Index (ESI). The MEDALUS model relies on these four core parameters—SQI, VQI, AQI, and CQI. Each parameter is classified into homogeneous categories based on its impact on the erosion process. The Erosion Sensitivity Index (ESI) is computed using the following formula (1):

$$ESI = \sqrt[4]{SQIxVQIxAQIxCQI} \qquad (1)$$

The parameters (SQI, VQI, AQI, CQI, and ESI) were determined using the dataset shown in Fig.3.

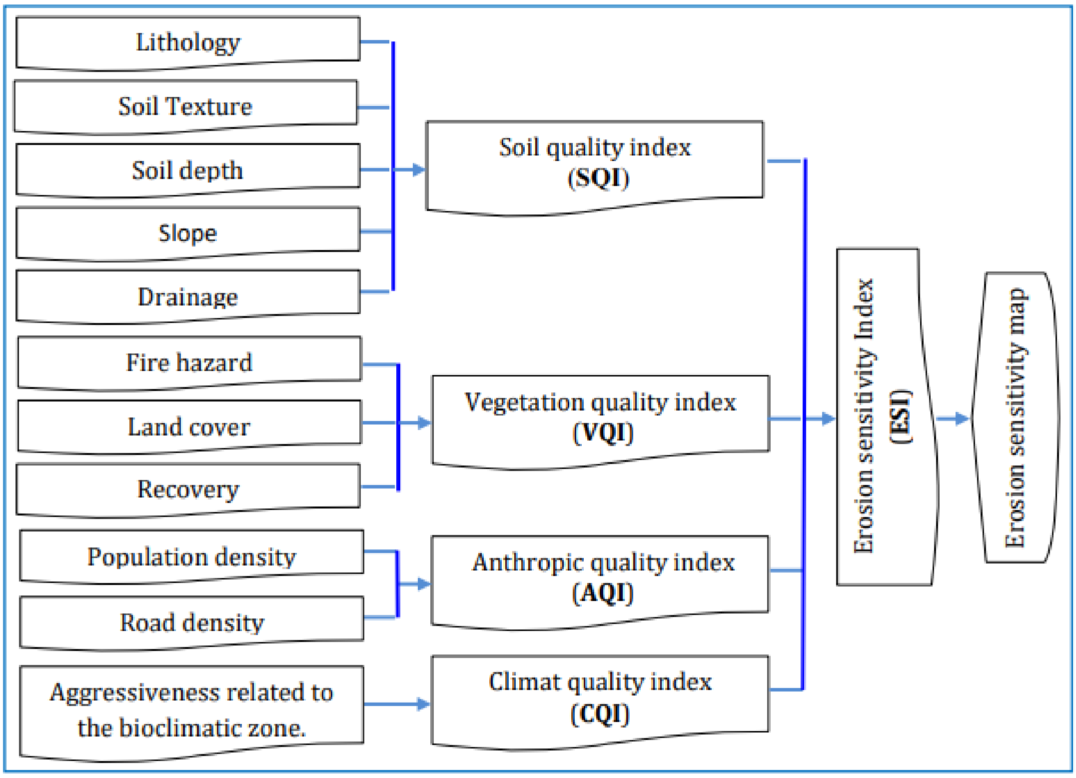


Figure 3: Illustrates the methodological diagram outlining the steps followed to calculate the ESI index.

The evaluation of soil vulnerability is based on the analysis of four key factors: soil quality, human quality, vegetation quality, and climatic quality.

These factors were carefully assessed to determine their contribution to the overall erosion sensitivity of the area.

Soil Quality Index – SQI

The variety of soil parameters influencing erosion makes it challenging to account for all of them comprehensively. Therefore, we have chosen to focus on a few simple and easily measurable parameters. The Soil Quality Index (SQI) is calculated using the following equation:

$$SQI = \sqrt[5]{L \; x \; T x \; S \; x \; D \; x \; Dd} \qquad (2)$$

Where L is the lithology index, T is the soil texture index, S is the slope index, D is the soil depth index, and Dd is the drainage density index. The slope map generated from the Digital Elevation Model (DEM) was reclassified according to the classification by Plaiklang et al. (2020) and converted into a soil erosion vulnerability map. The slope gradient is divided into four categories based on its influence on soil erosion. Regarding drainage, four distinct classes are defined to assess its effect (Boussaada et al. 2022; Prăvălie et al. 2020) (Tab. 3).

Table 3: Classification and Indices of SQI Parameters

Erosion factors	Class	Characteristic	Description	Score
Lithology	1	Hard limestone and dolomite, friable limestone	Good	1
	2	Conglomerates	Moderate	1.7
	3	Alluvium, sands and limestone crusts, sebkha	Poor	2
Depth	1	>75	Deep	1
	2	30-75	Moderate	2
	3	15-30	Shallow	3
	4	<15	Very shallow	4
Texture	1	L, LAS, LS	Good	1
	2	A, LA, AL, LAf, AS	Moderate	1.6
	3	SL, S	Poor	2
Slope	1	<6	Nearly level to flat	1
	2	6-12	Slightly sloping	1,2
	3	12-25	Moderately steep	1,5
	4	>25	Extremely steep	2
Drainage	1	Well drained	Good	1
	2	Medium-drained	Moderate	1,2
	3	Imperfectly drained	Poor	1,5
	4	Poorly drained	Very poor	2

Explanations: L = Loam, SCL = Sandy Clay Loam, SL = Sandy Loam, LS = Loamy Sand, SC = Sandy Clay, SiCL = Silty Clay Loam, C = Clay, SiC = Silty Clay, S = Sand.

Climate Quality Index – CQI

Climatic conditions play a crucial role in accelerating erosion processes. The key factors that amplify the erosion phenomenon include both the aggressiveness of the climate and the erosivity of precipitation, which are essential components of the Climate Quality Index (CQI).

The CQI estimates the amount of water available for plant growth (Prăvălie et al. 2020). The climate aggressiveness related to the bioclimatic zone refers to how climatic conditions influence ecosystems and human activities at different altitudes and latitudes. Bioclimatic zones are areas characterized by specific climatic conditions, which affect vegetation, wildlife, and human activities.

The pluviometric quotient (Q) or Emberger's climatic index is used to characterize the climate of a region, particularly in Mediterranean areas. This index takes into account temperature and precipitation to assess climatic conditions, helping to distinguish between different types of climates in Mediterranean regions, from very dry to very humid, based on the obtained values. The CQI was derived using the equation (3) below:

$$\boldsymbol{CQI = EB} \qquad (3)$$

Where EB is the score assigned to the bioclimatic zone. The assessment of climate aggressiveness is based on bioclimatic zones. From a bioclimatic perspective (Emberger's climatic index, Q), the study area is characterized by two main types of bioclimatic zones: the Upper Arid zone, which occupies the central and southeastern parts of the study area, characterized primarily by low and irregular rainfall and drought, and the Lower Arid zone, which occupies the south western part of the area (Tab.4).

Table 4: Classes and indices of the CQI parameters.

Erosion factor	**Class**	**Characteristic**	**Score**
Bioclimatic Zones	1	Q >40 (Upper Arid)	1
	2	Q < 40 (Lower Arid)	2

Source: Personal analysis in Arc gis software.

Anthropogenic Quality Index – AQI

He Anthropogenic Quality Index (AQI) was calculated based on two factors: Population Density (Dp) and Road Density (Dr). The formula for AQI is:(formula 4):

$$\boldsymbol{AQI = \sqrt[2]{Pd\ x\ Rd}} \qquad (4)$$

Population density in 2020 was categorized into four classes, while livestock density in 2020 was classified into three categories (Merdaset al.2021; Boussaada D et al.2022). Land use was divided into two distinct classes, as shown in Table 5.

Table 5 Classes and indices of the AQI parameters.

Erosion factors	Class	Characteristic	Score
Population density	1	<15 people/ km²	1
	2	15-20 people / km²	1,33
	3	20-50 people / km²	1,66
	4	>50 people / km²	2
Road density	1	<3 Km/km²	1
	2	3-7 Km/km²	1,5
	3	>7 Km/km²	2

Source: Personal analysis in Arc gis software.

Vegetation Quality Index – VQI

The preservation of soil quality is closely related to vegetation, whose impact on land degradation varies depending on its resistance to climatic changes and its ability to prevent soil erosion. The evaluation of the VQI was based on remote sensing methods applied to the interpretation of the satellite image acquired by Landsat 8, with a spatial resolution of 30 meters (formula 5):

$$\boldsymbol{VQI = \sqrt[2]{CLU\ x\ CV}} \quad (5)$$

Where CLU is Current Land Use data of the study area and CV is Coefficient of Variation of Plant Coverage. The image was analyzed to classify the various types of land use using ArcGIS 10.8. The parameters are evaluated on a scale of indices ranging from 1 (very good quality) to 2 (very poor quality), as shown in Tab. 6.

Table 6 Classes and indices of the VQI parameters.

Erosion factors	Class	Characteristic	Description	Score
Land use	1	Forest-maquis	High	1
	2	Steppe	Medium	1.5
	3	Shrub steppe	Low	1.75
	4	Bare soil and sand, cultivation	Very low	2
Coverage	1	>40%	High	1
	2	10-40%	Medium	1,8
	3	<10%	Low	2

Source: Personal analysis in Arc gis software.

To create the erosion sensitivity map, we calculated four quality indices by assigning scores to each parameter. Each index is derived from the geometric mean of the scores associated with the different parameters of the relevant factor (Tab.7). To assess the erosion sensitivity degree, we multiplied the quality indices of the four selected factors.

RESULTS AND DISCUSSION

Erosion sensitivity varies according to the quality of each indicator used in this approach (MEDALUS). Since our watershed is located in an arid region, environmental degradation in these areas mainly results from environmental factors, human activity, climatic variations, and factors related to the relief and topography of the land, lithology and soil structure, vegetation cover, and land use (Fig. 3).

Evaluation of land vulnerability factors to water erosion in the Boussada sub-basin

Soil Quality Index

The results obtained from calculating the soil quality index (Tab.7 & Fig. 4) reveal three distinct categories of soil quality: The category of good-quality soils is relatively limited in the region, representing about 21% of the total area. It is primarily associated with shrub formations and is characterized by soils composed of materials with balanced textures. The moderate-quality category is the most widespread, covering about 64% of the study area.

These soils are primarily found under steppe formations and generally have a medium to moderately deep depth. The poor-quality category occupies about 13% of the total area. It is less widespread. These soils are mainly found under shrub steppes and cultivation, primarily in the north-eastern part of the sub-basin. These classifications provide crucial information on the distribution and quality of soils in the studied region, which can be essential for land management and planning.

Table7: Distribution of the three Soil Quality Classes

SQI Classes	Rank	Area (Km²)	Area (%)
High	<1,13	590,57	20,09
Moderate	1,13-1,45	2063,63	70,24
Low	>1,45	284,16	09,67

Source: Personal analysis in Arc gis software.

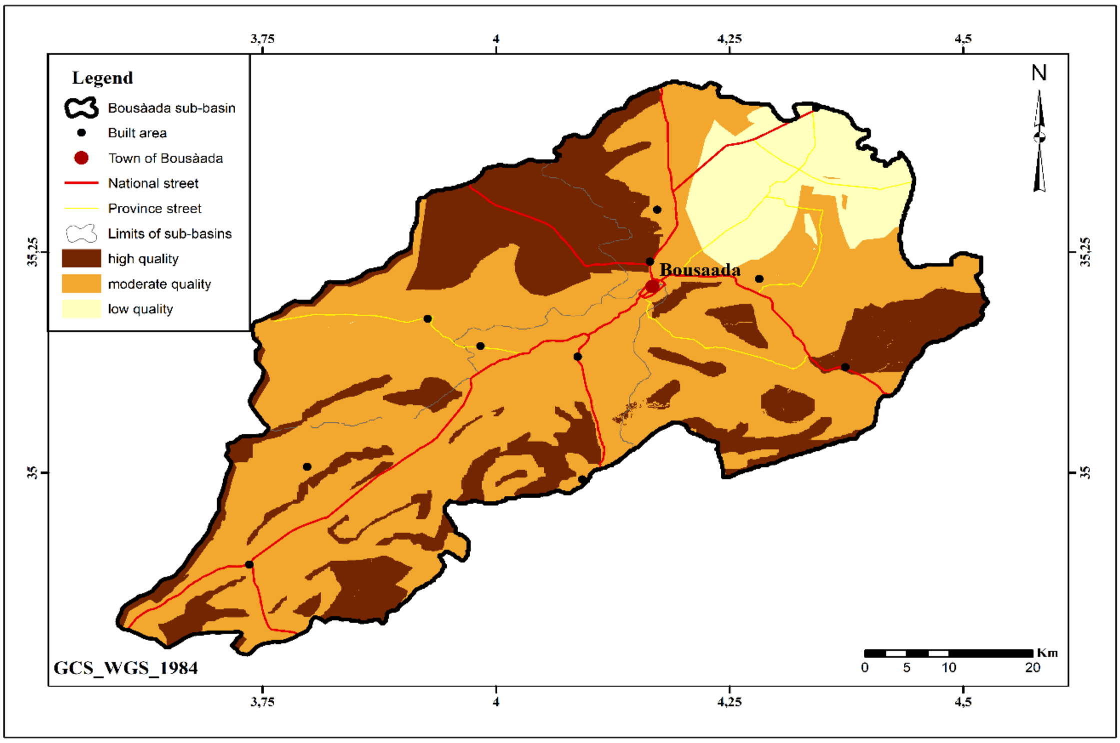


Figure 4. Soil Quality map.

Climatic Quality Index

The class of moderate climatic quality covers approximately 63% of the sub-basin area, located in the north-eastern part and corresponding to the lower arid bioclimate.

The class of poor climatic quality represents a very small portion of the total surface area (2.45%) of the sub-basin, situated in the extreme south of the region.

The results of the Climatic quality map (Fig. 5) primarily highlight three classes of climatic quality distributed (Tab. 8) as follows: The class of good climatic quality occupies nearly 35% of the sub-basin area, corresponding to the upper arid bioclimate. It is situated in the south-western part of the study area.

Table 8: Distribution of the three Climate Quality classes.

IQC Classes	Rank	Area(Km²)	Area(%)
High	≤1,49	1021,79	34,74
Moderate	1,49-1,90	1845,58	62,81
Low	≥1,90	71,99	2,45

Source: Personal analysis in Arc gis software.

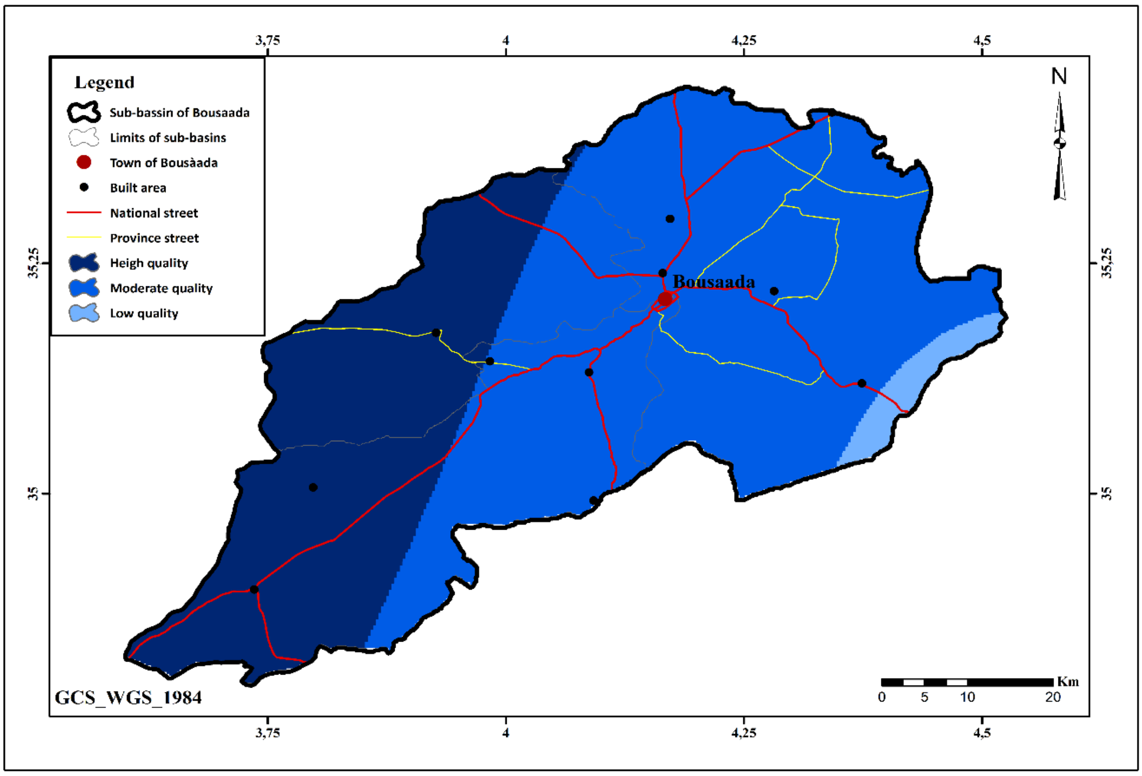


Figure 5. Climate Quality map.

Anthropogenic Quality Index

The map of the anthropogenic quality index (Fig.6) reveals that the majority of the Boussaada sub-basin (78%) exhibits poor quality. This situation is mainly attributed to overgrazing in pastoral lands and urban expansion, which have a negative impact on the quality of developments.

Meanwhile, areas of good quality (9%) and moderate quality (12%) correspond to shrub formations and cultivated lands (Tab. 9).

Table 9: Distribution of the three Anthropogenic Quality classes.

AQI Classes	Rank	Area(Km²)	Area(%)
High	≤1,22	1192,57	40.57
Moderate	1,22-1,44	1623,41	55,25
Low	≥1,44	122,38	04,18
Source: personal analysis in Arc gis software.			

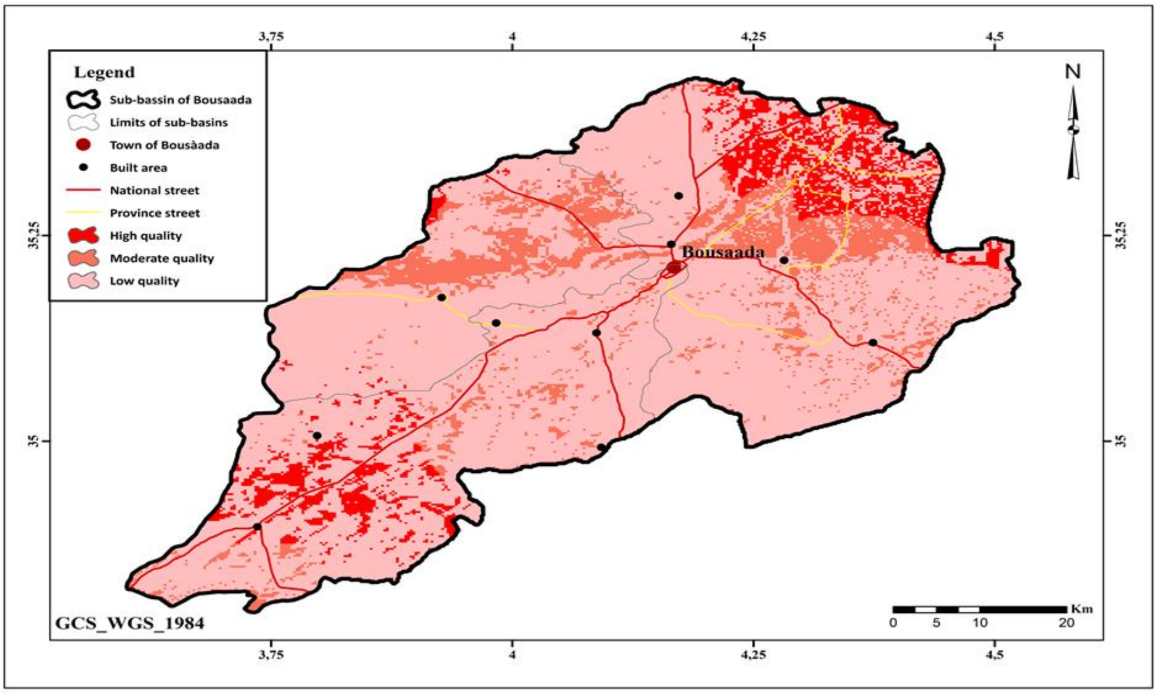


Figure 6.Anthropogenic Quality map.

Vegetation Quality Index

The map of the vegetation quality index (Fig.7) reveals three classes (Tab. 10) distributed as follows: Areas with good vegetation quality are generally found in mountainous forest regions, occupying approximately 39% of the total area, this class is mainly characterized by shrub vegetation forming a significant barrier against erosion, the class of vegetation with moderate quality covers about 15% of the sub-basin area. It is less widespread and corresponds to shrub steppes and cultivated areas and the class of poor-quality vegetation represents nearly 48% of the total area. This is the most widespread class in the Boussaada sub-basin, corresponding to degraded steppes and desertified lands.

Table 10: Distribution of the three Vegetation Quality classes.

VQI Classes	Rank	Area(Km²)	Area(%)
High	≤1,23	19,86	00,67
Moderate	1,23-1,44	919,59	31,30
Low	≥1,44	1998,91	68,03

Source: Personal analysis in Arc gis software.

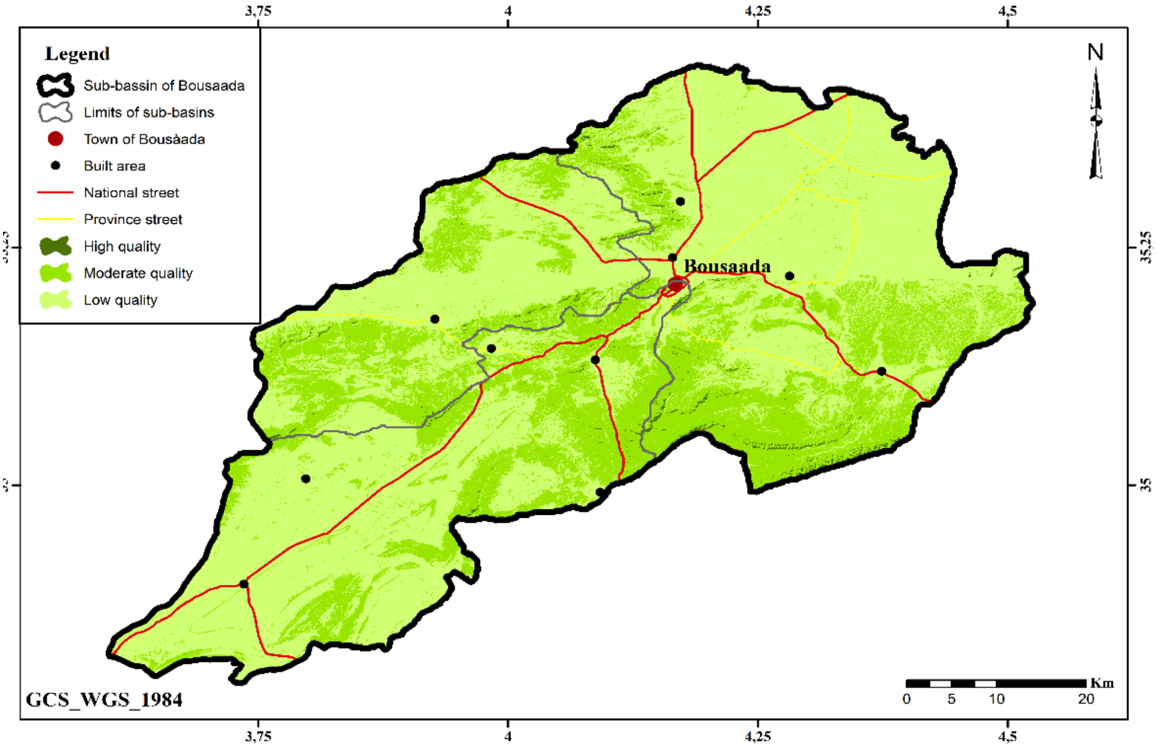


Figure 7: Vegetation Quality map.

Map of Erosion Sensitivity Index (ESI)

Figure 8 illustrates the map highlighting the erosion sensitivity across different areas of the Boussaada sub-watershed. The application of the MEDALUS method enabled us to evaluate the degree of erosion sensitivity within the Boussaada sub-basin.

Table 11 showed four zones of erosion sensitivity were distinguished: very sensitive, sensitive, moderately sensitive, and non-sensitive.

Table 11: Erosion Sensitivity Index (ESI)

ISE Classes	Rank	Area(Km²)	Area(%)
Not sensitive	<1,26	615,76	17.37
Slightly sensitive	1,26 -1,38	360,77	10,18
Moderately sensitive	1,38-1,53	1348,12	38,03
Highly sensitive	>1,53	1220,26	34.42

Source: Personal analysis in Arc gis software.

The erosion sensitivity map (Fig. 8) shows that a large part of this sub-basin is classified as highly to very sensitive to erosion, occupying nearly 72% of the total area. This classification is explained by the arid climate of the region and inappropriate land management, which has led to a predisposition to erosion. Areas moderately sensitive to erosion represent approximately 10% of the study area and are mainly located at the northern and southern ends of the sub-basin. Areas less sensitive to non-sensitive to erosion cover only 17% of the mapped area of the Boussaada sub-basin. They are mainly found in mountainous areas where the quality of soil and vegetation is relatively good, reducing their sensitivity to erosion.

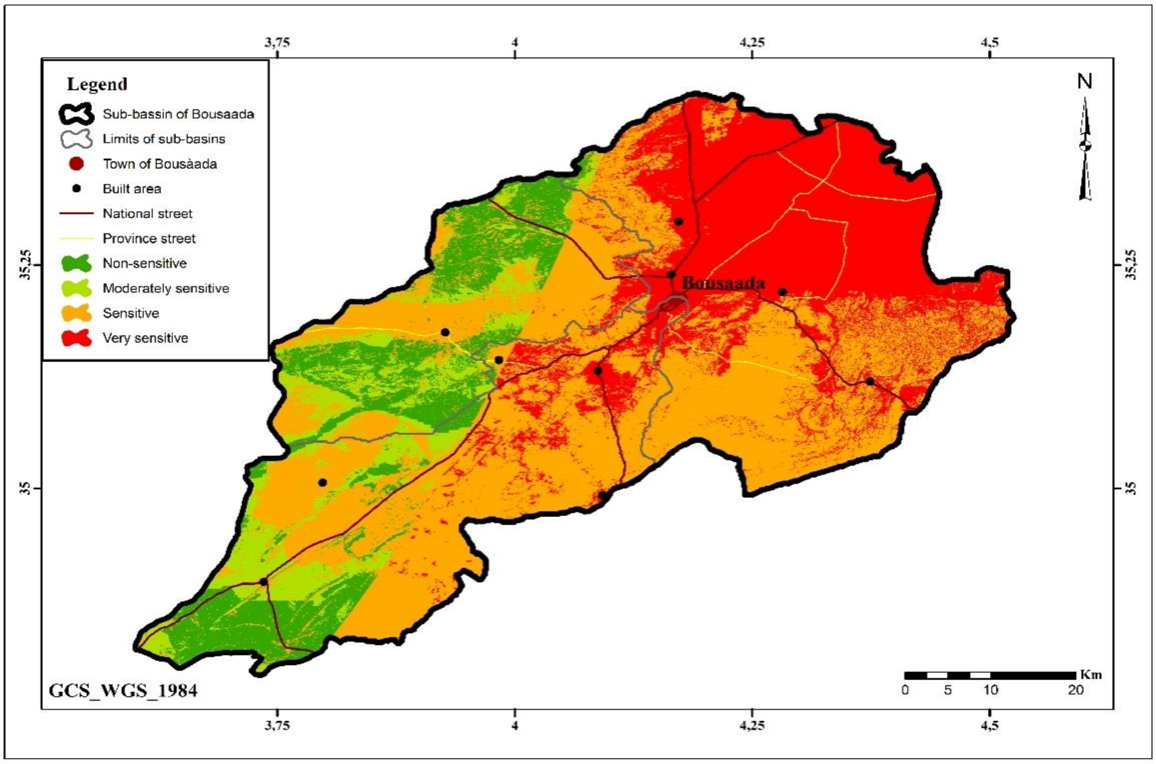
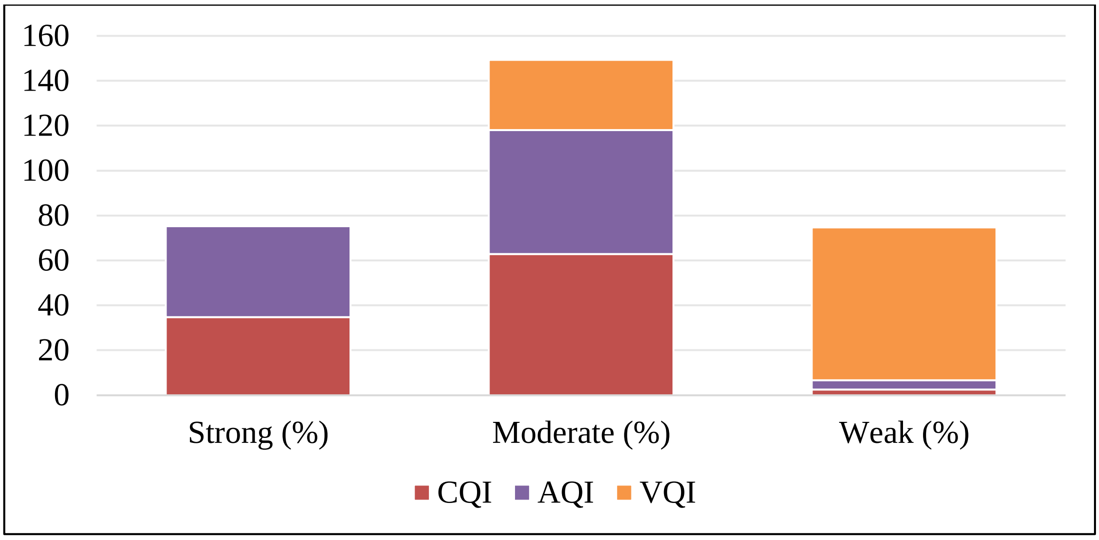


Figure 8: Map of the Erosion Sensitivity Index (ESI) in the Boussaada sub-basin



Graph 1: Correlation distribution with ESI / **From** Personal analysis in Arc gis software.

This study provides a comprehensive analysis of how different quality indices—climate, anthropogenic, and vegetation—relate to erosion sensitivity in the region. The findings highlight the complex interactions between natural and human-induced factors that contribute to erosion risk, offering valuable insights for effective erosion management strategies (Hirche et al. 2007).

The Climate Quality Index (CQI) demonstrated a strong relationship with erosion sensitivity across the study area. The majority of the region showed moderate (62.81%) to strong (34.74%) correlations, covering a significant area of 1845.58 km² and 1021.79 km², respectively. Only a small portion (2.45%) exhibited a weak correlation (71.99 km²). This indicates that climate, including factors such as temperature and precipitation, plays a crucial role in determining areas most susceptible to erosion. The high percentage of moderate and strong correlations suggests that climatic conditions are a dominant factor in influencing erosion sensitivity (Boussaada et al. 2022).

Similarly, the Anthropogenic Quality Index (AQI), which reflects human impact on the landscape, follows a similar pattern to the CQI. A significant portion of the study area shows a moderate correlation (55.25%) with erosion sensitivity, covering 1623.41 km², while 40.57% of the area is strongly correlated (1192.57 km²). Only a small area (4.18%) shows weak correlation (122.38 km²). These findings underscore the significant influence of human activities such as deforestation, urbanization, and agriculture on the landscape’s susceptibility to erosion. Like climate, human activities are a primary driver of erosion sensitivity in the region (Boussaada et al.2022).

In contrast, the Vegetation Quality Index (VQI) reveals a different trend. A large portion of the study area shows a weak correlation (68.03%) between vegetation quality and erosion sensitivity, covering 1998.91 km², while 31.30% demonstrates a moderate correlation (919.59 km²), and only a very small area (0.67%) shows a strong correlation (19.86 km²). This inverse relationship suggests that areas with low vegetation quality are particularly vulnerable to erosion, while regions with better vegetation cover may experience less erosion. The results imply that improving vegetation quality, especially in areas with weak correlation, could be an effective strategy for reducing erosion risk (Hirche et al. 2007).

The Erosion Sensitivity Index (ESI), which combines the effects of climate, human impact, and vegetation, provides a comprehensive view of erosion risk across the region. The analysis indicates that 38.03% of the area (1348.12 km²) is moderately sensitive to erosion, while 34.42% (1220.26 km²) is highly sensitive. A smaller portion (17.37%, 615.76 km²) is classified as not sensitive, and 10.18% (360.77 km²) falls under slight sensitivity. This distribution emphasizes that over 72% of the study area is at moderate to high risk of erosion, indicating the urgent need for targeted erosion control measures (Boussaada et al. 2022; Hirche et al., 2007).

CONCLUSION

Erosion, driven by both natural and human factors, poses a significant threat to environmental sustainability and community resilience against climate change. This study used the MEDALUS model to assess soil erosion sensitivity, providing a comprehensive understanding of the factors contributing to soil degradation. The Erosion Sensitivity Index (ESI) revealed varying levels of vulnerability, with regions exhibiting low sensitivity benefiting from favorable climatic conditions, minimal human intervention, and healthy vegetation, which are crucial for preventing erosion.

The majority of the study area, however, falls under the Moderately Sensitive and Highly Sensitive categories, with 34.42% classified as Highly Sensitive. These areas are vulnerable due to harsh climatic conditions, human pressure, and poor land management practices like overgrazing and inadequate farming methods, which accelerate desertification. The Anthropogenic Quality Index (AQI) demonstrated that regions with high human impact face higher erosion risks, while areas with low human disturbance are more resistant to erosion. Similarly, the Vegetation Quality Index (VQI) showed that regions with poor vegetation cover are more prone to erosion, particularly in arid zones.

The erosion sensitivity map created through this analysis is an essential tool for prioritizing intervention areas. Regions with high sensitivity should focus on conservation measures such as reforestation, sustainable farming, and improving land management practices. Areas with moderate soil quality, which cover a significant portion of the study area, need preventive interventions to maintain soil health and avoid further degradation. Ultimately, this GIS-based approach using the MEDALUS model supports effective land management decisions and provides a roadmap for combating soil erosion, improving productivity, and addressing desertification.

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